Research on Custody Transfer Service in Delay Tolerant Network

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Abstract—A delay/disruption tolerant network (DTN) architecture was proposed to effectively support communication in challenging scenarios characterized by intermittent connectivity and long latency. The custody transfer (CT) mechanism is used to improve the reliability of DTN. We proposed a mathematical model of the DTN data link. Based on this model, we simplified a link containing both nodes with and without CT into a link containing only nodes with CT. We developed a NS2-based DTN simulator and conducted three simulations. The first two simulations are conducted on links whose hops are from 2 to 10, where all relay nodes accept or deny CT. The simulation results show that the destination node receives far more data when CT is available; furthermore, the storage consumption of the source node decreases. The third simulation is conducted to evaluate the effect of retransmission timer on storage consumption and retransmission times. The simulation results show that the value of retransmission timer that is greater than the maximum round-trip-time between adjacent nodes and less than the minimum disconnection interval is a good candidate for DTN data transfer.

Index Terms—Delay/Disruption Tolerant Network; Custody Transfer; Network Model; Network Simulation

I. INTRODUCTION

Existing TCP/IP protocols are ineffective in challenging scenarios that are characterized by long propagation delays, intermittent connectivity, and high data loss rates, such as those encountered in interplanetary communication. To deal with such scenarios, a delay/disruption tolerant network (DTN) architecture was proposed [1] [2].

The DTN architecture defines a message-oriented overlay called the bundle layer that operates at a layer above the transport layer and below the application layer (Fig. 1). The bundle layer focuses on virtual message forwarding rather than packet switching. Therefore, multiple transport layer protocols may be implemented on different nodes in a DTN. Most services provided by the bundle layer are typically unacknowledged; to counter this, the DTN architecture proposes a store-and-forward mechanism called custody transfer (CT) that affords improved communication reliability. Owing to increased interest and potential applications in this area, the concept of DTN is being extended to the delay/disruption tolerant network. Research in DTNs is being extended from the Interplanetary Network (IPN) to other types of networks that feature similar challenging operating conditions, e.g., wireless sensor networks (WSNs) [3] [4] and mobile ad hoc networks (MANETs) [5] [6].

A series of protocol drafts, including Delay-Tolerant Networking Architecture (RFC4838) [7], Bundle Protocol Specification (RFC5050) [8], and Linklider Transmission Protocol Specification (RFC5236) [9], was released by the DTN Research Group (DTNRG) of the Internet Research Task Force (IRTF). The Consultative Committee for Space Data Systems (CCSDS) has also made great efforts to promote the use of the DTN architecture for future deep-space missions [10]. Some modified versions of these standards, such as the CCSDS Bundle Protocol Specification [11], have already been released.

Figure 1. Internet layers vs. DTN layers. The bundle layer is an overlay operates at a layer above the transport layer and below the application layer.

In recent years, space agencies have conducted numerous experimental flight tests. The first DTN architecture test in space was conducted in 2008, using the United Kingdom Disaster Monitoring Constellation (UK-DMC) satellite in low earth orbit [12]. In the same year, the Jet Propulsion Laboratory (JPL) installed and tested DTN technology on the Deep Impact Network Experiment (DINET) [13]. DINET is an interplanetary network that contains two mars surface assets, a relay orbiter (the Deep Impact spacecraft) and the earth. The DTN architecture was deployed on the International Space Station in 2009 [14]. A bundle protocol agent was installed to the Commercial-Grade Bioprocessing Apparatus 5 (CGBA5), which is a life science payload on ISS and has an embedded communication platform. The DTN architecture is expected to play an important role in future deep-space communications.
In the area of DTN, numerous studies have already focused on routing [15] [16], congestion control [17] [18], security [19] [20], and other issues [21]. However, few studies have focused on CT. In this study, we evaluate the performance of CT when applied to a DTN data link, with a particular focus on its effect on storage consumption. We establish a mathematical model of the DTN data link. Based on this model, we propose a method to simplify a link containing both nodes with and without CT into a link containing only nodes with CT. Then, simulations with and without CT were conducted to investigate the effectiveness of CT for DTN communications.

The remainder of this paper is structured as follows. Section II overviews the CT mechanism in DTN. Section III presents the mathematical model of the DTN data link. Section IV presents the analysis of the simulation results and the discussion. Finally, Section V presents the conclusions of this study.

II. CT IN DTN

Owing to the fact that DTNs are often characterized by intermittent connectivity, continuous end-to-end connectivity may not be possible. Therefore, DTN protocol data units (called bundles) may need to be stored in one or more DTN nodes. As a result, DTN nodes are required to provide persistent storage to bundles.

The node that provides CT to a bundle is called the bundle’s Custodian. The custodian node should keep a copy of the bundle in its persistent storage and promise not to discard it until (a) another node provides CT for it, (b) the bundle reaches its destination node, or (c) the bundle expires. A retransmission timer is set when the custodian node sends a bundle to the next node. If the next node agrees to provide CT to a received bundle, it sends a custody acknowledgement to the bundle’s former custodian. If no acknowledgement is received before the retransmission timer expires, the sender needs to retransmit the bundle.

Ordinarily, there should be only one copy and one custodian for a bundle. However, in some circumstances, for instance, loss of custody acknowledgement or lack of return channel, there might exist more than one copy or custodian. In this situation, the custodian will keep the copy and try to retransmit it until an acknowledgement is received or the bundle expires.

It should be noted that not all DTN nodes have to provide CT. Whether DTN nodes accept custody of a bundle is an implementation issue that depends upon resource or policy considerations. A node may provide CT when it has plenty of free storage, and it may deny CT when its storage is relatively full.

III. MATHEMATICAL MODEL OF DTN DATA LINK

It is difficult to conduct network analysis using traditional methods because of the fact that a DTN is often characterized by intermittent connectivity. We redefine the following parameters to build the DTN data transfer model:

- **D(t)**, delay parameter: \( D_{B,A}(t) \) is the latency between a bundle being sent by node A at time t and its arrival at node B, ignoring blockages that may exist between nodes A and B. \( D_{A,B}(t) \) and \( D_{A,B}(t) \) are not equal in some cases owing to the relative movement between the nodes. In deep-space communications, delay jitter caused by relative movement between DTN nodes is usually negligible to the inherent delay between nodes. For instance, jitter that in communication between a Mars orbiter and Earth stations is less than 0.1 s, while the communication delay between Mars and Earth is more than 4 minutes. For simplicity, \( D_{B,A}(t) \) and \( D_{A,B}(t) \) are considered equivalent as a constant \( D_{B,A} \) in this study.

- **H(t)**, connectivity parameter: \( H_{B,A}(t) \) is a two-value parameter used to represent whether the bundles sent by node A at time t can be received by node B (after a delay of \( D_{B,A} \)). \( H_{B,A}(t) \) is set to 1 when the bundle can be received successfully by node B, and 0 otherwise.

\[
H_{B,A}(t) = \begin{cases} 
1 & \text{when bundles can be received} \\
0 & \text{when bundles cannot be received} 
\end{cases}
\]

\( H_{B,A}(t) \) may not be equal to \( H_{A,B}(t) \) owing to obstructions or some other effects in deep-space communication.

- **BW(t)**, bandwidth: \( BW_{B,A}(t) \) is the maximum number of bundles that node A can send to node B in unit time. Generally, \( BW_{B,A}(t) \) is not equal to \( BW_{A,B}(t) \) — the downlink bandwidth is far greater than the uplink bandwidth in deep-space communication.

In addition, Link \([1,2,\ldots,N]\) is defined as a symbol of the DTN data link through which bundles are sent from node 1 to node N via node 2, node 3, ..., node N-1 successively.

The length of bundles may be variable according to RFC5050. However, in a stable communication period, a fixed bundle length is thought to be benefit to data delivery and management. Assuming that the length of the bundles and the custody acknowledgements are set to 1 Mbit and 1Kbit respectively, if a custody acknowledgement is provided for each bundle, the ratio between downlink bandwidth and uplink bandwidth can reach 1024 in a DTN. Actually, we can use 1 bit in custody acknowledgement to indicate whether a bundle is successfully transferred. In this case, the ratio between downlink bandwidth and uplink bandwidth can reach 10^6.

The DTN that has no reverse link is not mentioned in this study. And the reverse link is supposed to be sufficient to transfer acknowledgements.

A. Mathematical Model of 2-node DTN Data Link

In a simple two-node DTN data link, Link \([A, B]\), the data-transfer activity can be described from the perspective of nodes A and B, respectively. Node A lays greater emphasis on the amount of data that has already been sent that can be successfully received by node B (in the future); node B lays greater emphasis on the amount of data that has been received.

From the perspective of node A, the amount of data that can be received by node B successfully at time t is
From the perspective of node B, the amount of data that has already been received successfully at time $t$ is

$$DS_{B,A}(t) = \int_0^t BW_{B,A}(t)H_{B,A}(t)dt$$  \hspace{1cm} (2)$$

B. Mathematical Model of $N$-node ($N>2$) DTN Data Link

DTN nodes are divided into A-type and B-type nodes that respectively provide and do not provide CT to bundles. A common DTN data link is composed of both A-type and B-type nodes (Fig. 2.1).

Assuming that node 2 of Link [1, 2, 3] is a B-type DTN node, bundles received by node 2 will be transmitted immediately to node 3 when Link [2, 3] is available, otherwise they will be dropped. Whether a bundle can be transferred successfully to node 3 is determined by the status of both Link [1, 2] and Link [2, 3]. The disconnection of either Link [1, 2] or Link [2, 3] will lead to data transmission failure. Only when both $H_{2,1}(t)$ and $H_{1,2}(t+D_{2,1})$ are equal to 1 can bundles be successfully transferred to node 3. The data-transfer rate is determined by the smaller of $BW_{2,1}(t)$ and $BW_{2,1}(t+D_{2,1})$.

This means that a three-node DTN data link in which the relay node does not provide CT can be simplified as an equivalent two-node DTN data link:

$$DS_{A,1}(t) = \int_0^t BW_{A,1}(t)H_{A,1}(t)dt$$  \hspace{1cm} (4)$$

$$DR_{A,1}(t) = \int_{D_{A,1}}^{t-D_{A,1}} BW_{A,1}(t-D_{A,1})H_{A,1}(t-D_{A,1})dt$$  \hspace{1cm} (5)$$

For the equivalent two-node DTN data link, the link parameters are

$$H_{A,1}(t) = H_{A,2}(t+D_{A,2})H_{2,1}(t)$$

$$BW_{A,1}(t) = \min(BW_{2,1}(t), BW_{2,1}(t+D_{2,1}))$$

$$D_{A,1} = D_{A,1} + D_{2,1}$$

The above equations can be extended to an N-node DTN link in which all relay nodes do not provide CT:

$$DS_{N,1}(t) = \int_0^t BW_{N,1}(t)H_{N,1}(t)dt$$  \hspace{1cm} (6)$$

$$DR_{N,1}(t) = \int_{D_{N,1}}^{t-D_{N,1}} BW_{N,1}(t-D_{N,1})H_{N,1}(t-D_{N,1})dt$$  \hspace{1cm} (7)$$

The parameters of the equivalent link are

$$H_{N,1}(t) = H_{2,1}(t) \prod_{m=2}^{N-1} H_{m+1,m}(t+\sum_{i=1}^{m-1} D_{i+1,i})$$  \hspace{1cm} (8)$$

According to the above discussions, irrespective of the number of B-type nodes between two adjacent A-type nodes, the link can be simplified into a direct connection between two A-type nodes. Hence, an ordinary DTN link Link [1,2,…,N] that is composed of both A-type and B-type nodes can be simplified into a link Link [1,2,…,M] that is composed of only A-type nodes. For adjacent nodes $m$ and $m+1$ (1 ≤ $m$ ≤ $M$) in Link [1,2,…,M], DS and DR in time interval [0, T] can be calculated as follows:

$$DS_{m+1,m}(T) = \int_0^{T-D_{m+1,m}} BW_{m+1,m}(t)H_{m+1,m}(t)dt$$  \hspace{1cm} (11)$$

$$DR_{m+1,m}(T) = \int_{D_{m+1,m}}^{T-D_{m+1,m}} BW_{m+1,m}(t-D_{m+1,m})dt$$  \hspace{1cm} (12)$$

In a DTN, the transmission latency between adjacent nodes cannot be ignored. In a specific communication period [0, T], the data transfer between nodes A and B would have invalid regions, as shown in Fig. 3. Bundles in invalid region I may be received after time T. However, if time T is the end time of a contact and the link will not be available again in $D_{B,A}$, all the bundles in region I will be lost. Bundles in region II (if any) were sent by node A before time 0. If time 0 is the start time of a contact and node A has not sent the bundles to node B before, no bundle in region II can be received by node B.

The existence of invalid regions narrows the available communication interval of relay nodes. In Link [1,2,…,M] that is composed of only A-type nodes, the available communication interval of relay node $m$ (1 $< m$ $< M$) is shortened from [0,T] to [$\sum_{i=1}^{m-1} D_{i+1,i}$, $T - \sum_{i=1}^{m-1} D_{i+1,i}$]. The greater the distance between node m and the source node, the more does region I affect the available communication interval. Furthermore, the greater the distance between node m and the destination node, the more does region II affect the available communication interval.
For the existence of invalid regions, the upper and lower limits of (10) and (11) should be modified as follows:

\[ DS_{m+1,m} (T) = \int_{0}^{T} \sum_{j=m}^{m+1} D_{m,j} \cdot BW_m (t) H_{m+1,m} (t) dt \]  
\[ DR_{m+1,m} (T) = \int_{0}^{T} \sum_{j=m}^{m+1} D_{m,j} \cdot BW (t - D_{m+1,m}) H (t - D_{m+1,m}) dt \]  

(13)  
(14)

According to (12) and (13), it is easy to notice that in a specific communication interval [0, T], \( DS_{m+1,m} (T) \) and \( DR_{m+1,m} (T) \) are equal. This is in agreement with actual situations.

The amount of bundles that can be transferred successfully through the entire link cannot be greater than the minimum amount of bundles that can be transferred successfully between any two adjacent nodes:

\[ DS_{m+1,m} (T) \leq \min (DS_{2,1} (T), DS_{3,2} (T), \ldots, DS_{N,N-1} (T)) \]  

(15)

Equation (14) indicates the theoretical upper limit of the amount of bundles that can be transferred via a DTN data link. It is difficult for the equality in (14) to hold because of the fact that DTN networks are characterized by intermittent connectivity. As a result, \( DS_{m+1,m} (T) \) typically cannot reach the theoretical limit of \( \min (DS_{2,1} (T), DS_{3,2} (T), \ldots, DS_{N,N-1} (T)) \). However, in some specific situations, the equality always holds, e.g., in the situation that the connections between any two adjacent nodes are always reliable. Meanwhile, the bandwidth between any two adjacent nodes is invariable.

IV. SIMULATION RESULTS

To study the key features of DTN, we developed an NS2-based DTN simulator called DS-NS2 (DTN simulator on NS2) using C++ and OTcl. The bundle handling procedure of DS-NS2 strictly obeys RFC5050.

Three simulations in all were conducted. In the first two simulations, we evaluated the CT performance in a DTN link with 11 nodes, Link [0,1,...,10]. They were conducted to investigate storage consumption in the cases with and without CT. The link parameters are listed in Table I. The bundle length \( s \) is set to 1 Mbit, and all bundles have the same priority. Each node has only one chance to connect to next node.

In the third simulation, we evaluated the performance in a DTN link with 3 nodes, Link [A, B, C]. The simulation was conducted to investigate how retransmission timer affects storage consumption and retransmission times with CT. Link parameters for simulation 3 are listed in Table II. The bundle length \( s \) is set to 1 Mbit, and all bundles have the same priority. Each node has only more than one chance to connect to next node.

A. Data Link without CT

In the first simulation, none of the relay nodes provide CT. Actually; the first simulation includes 10 simulations in which the destination nodes are designated as nodes 1–10 in order. In other words, the first simulation contains 10 DTN links whose hop numbers are 1–10.

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Start time</th>
<th>End time</th>
<th>BW</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>3600</td>
<td>46800</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>7200</td>
<td>50400</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>10800</td>
<td>54000</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>14400</td>
<td>57600</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>18000</td>
<td>61200</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>21600</td>
<td>64800</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>25200</td>
<td>68400</td>
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<td>60 s</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>28800</td>
<td>72000</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>32400</td>
<td>75600</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>36000</td>
<td>79200</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
</tbody>
</table>

Data is generated at the source node at a rate of 800 Kbps, which is equal to the bandwidth between any two adjacent nodes, so that the storage consumption of the source node remains the same when the source node begins to release its stored data after receiving the custody signals. The source node, node 0, has a storage space of 32 Gbit. Other nodes have 8 Gbit storage space when they serve as relay nodes or unlimited storage space when they serve as destination nodes. The lifetime of each bundle is set to 86400 s to ensure that no bundle expires during the simulation. The custody retransmission timers are also set to 86400 s to ensure that no bundle is retransmitted.

Figs. 4 and 5 respectively show the storage consumption of the destination and the source nodes.

![Figure 4. Destination node storage consumption (without CT).](image-url)
takes 84991 s to reach its storage limit. On the other hand, when node 10 is the destination node, the source node takes only 51526 s to reach its storage limit.

B. Data Link with CT

In the second simulation, the same configuration as in the first simulation is employed, except for the fact that CT is available—all relay nodes (nodes 1–10) provide CT. Figs. 6 and 7 respectively show the storage consumption of the destination and the source nodes.

Although the latencies are different, all destination nodes receive the same amount of 33692 Mbit of data by the end of simulation 2 (Fig. 6). This amount of data is equal to the amount that can be transferred successfully between any two adjacent nodes. The equality in (14) holds in this situation.

Irrespective of the length of the data link, the storage space of the source node is consumed at the same rate (Fig. 7) because the link state between nodes 0 and 1 is the only factor affecting the storage consumption of the source node when CT is available.

Fig. 8 shows the storage consumption of the relay nodes in the 10-hop situation. Node 1 starts to receive bundles at 3660 s and reaches the maximum of 2856 Mbit at 7320 s. Node 0 disconnects from node 1 at 46800 s, and the amount of data stored in node 1 decreases until node 2 disconnects from node 1 at 50400 s. It is noteworthy that node 1 does not become empty after 50400 s because some acknowledgements are lost after the disconnection. Other relay nodes show the same behavior as node 1 but with different latencies.

C. Retransmission Timer

In the third simulation, the performance is evaluated on a 3-node DTN link, Link [A, B, C]. The data generation rate, storage space, and bundle lifetime are employed the same as configurations in simulation 1. The retransmission timer value varies between 160 and 46800 s.

Figs. 9 and 10 respectively show the storage consumption of the relay and the source nodes.

Fig. 9 shows that a proper retransmission timer value is beneficial to utilize the relay node storage space effectively.
TABLE II. DATA LINK PARAMETERS FOR SIMULATION 3

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Start time</th>
<th>End time</th>
<th>BW</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>0</td>
<td>3600</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>7200</td>
<td>14400</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>21600</td>
<td>32400</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>43200</td>
<td>57600</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
<td>72000</td>
<td>90000</td>
<td>800 Kbps</td>
<td>60 s</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td>3600</td>
<td>7200</td>
<td>800 Kbps</td>
<td>120 s</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td>10800</td>
<td>18000</td>
<td>800 Kbps</td>
<td>120 s</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td>25200</td>
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<td>120 s</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td>46800</td>
<td>61200</td>
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<td>120 s</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td>75600</td>
<td>90000</td>
<td>800 Kbps</td>
<td>120 s</td>
</tr>
</tbody>
</table>

A smaller value than the round-trip-time (RTT) leads to more storage consumption, because the timer expires before any custody acknowledgement for the bundle can be received. Each bundle is sent at least 2 times by the relay node when the timer is set to 160 s. This makes an inefficient utilization of the forward link. Timer values between 320 s and 3600 s seem to be proper options in the simulation for their low storage consumptions. For values greater than 7200 s, none of the timers expires in the first contact between 3600 s and 7200 s. Furthermore, the second contact is waste when value of the retransmission timer is greater than 28800 s. Buffer overflows at about 24000 s when the retransmission timer value is greater than 28800 s.

A proper timer value should lead to low storage consumption and ART. The value of the retransmission timer that is greater than the maximum RTT between any adjacent nodes and less than the minimum disconnection interval should be a good candidate according to above discussions.

Fig. 10 shows that a proper retransmission timer value is benefits to utilize the source node storage space effectively. Timer values between 320 s and 14400 s seem to be proper options in the simulation for their low storage consumptions. Though the 160-second timer value is greater than the RTT, it utilizes the storage inefficiently after when buffer of the relay node overflows at about 28000 s. Timers whose value is greater than 28800 s make things even worse.

Fig. 11 shows the average retransmission times (ART) of source and relay nodes. ART is the ratio between the amount of bundles sent by the sender and the amount of bundles received successfully by the receiver with no duplicates. The 160-second timer, as discussed above, leads to far greater ART than the others. Timer values from 960 to 14400 s provide satisfactory ARTs.

V. CONCLUSIONS

This study focuses on the CT performance in a DTN. We propose a mathematical model of a DTN data link by redefining the delay, connectivity, and bandwidth parameters. In this model, the data link contains both nodes with and without CT—this can be simplified into a link that contains only nodes with CT. The insertion of nodes without CT will cause a decline in the link parameters or even disconnection of the data link. The results of simulation 1 and 2 show that the data link containing nodes with CT will achieve better performance than a link containing nodes without CT. CT increases the amount of bundles received at the destination node and reduces the space occupation of the source node considerably. And the result of simulation 3 shows that a proper value of transmission timer should be
set greater than the maximum RTT between adjacent nodes and less than the minimum disconnection intervals.

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